A New CMOS-Integrated Analog Lock-In Amplifier for Automatic Measurement of Very Small Signals

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1 Introduction

In sensor applications, sometimes it is important to reveal and measure very low physical/chemical quantities, also with high accuracy and precision [1–3]. This can be achieved through the optimization/maximization of the measurement system sensitivity and resolution. In particular, in the case of small and noisy signals, coming from sensors, the lock-in technique, which is able to extract the signal from noise, can be taken into account. More in general, commercial lock-in amplifiers, as well as ad hoc solutions proposed in the literature also applied in sensor interfacing, are mainly of digital kind and, even if they show good performances and are particularly suitable for multifrequency operations, have high costs, weights, and sizes. On the contrary, in sensor applications, the analog kind of the signal to be revealed suggests, especially when the SNR is less than unity, the use of analog lock-in systems [4–9]. Unfortunately, both analog and digital traditional lock-in amplifiers have the disadvantage of knowing or fixing the operating frequency and requiring, at power on, the initial nulling of the output signal, which corresponds to the "in-quadrature" condition between input and reference signals (this should be also guaranteed continuously during the measurements). Then, the manual activation of switches provides a further 90° phase shift, allowing the reading of the output voltage, proportional to input mean value. In addition, if an operating frequency variation occurs, the system requires an additional calibration or, in worst cases, the redesign of internal blocks (e.g., band-pass filters).

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In this sense, here we present a new automatic analog lock-in amplifier suitable for the accurate measurements of very small signals coming from sensors, corresponding to low physical/chemical quantities. The circuit represents an advance (patented [7]) of the topology already proposed in [8] and [9]. This system operates automatically and continuously the relative phase alignment and the frequency tuning of input noisy and reference signals, both at power on and when a variation (of the phase and/or the operating frequency) occurs so allowing the correct detection of the mean value of the small input noisy signal.

2 The Proposed Automatic Lock-In Amplifier

The complete analog system, whose block scheme is shown in Fig. 1, has been implemented firstly as a prototype PCB and, successively, also designed and fabricated in a standard CMOS technology (AMS 0.35 μm) as an integrated chip, whose photo is reported in Fig. 2, with single supply voltage (1.8 V), reduced power consumption (lower than 2 mW), low costs, and small weights and sizes. The system has been optimized to operate in the working frequency range (2.5 ÷ 25) Hz, which is suitable for different sensor applications.

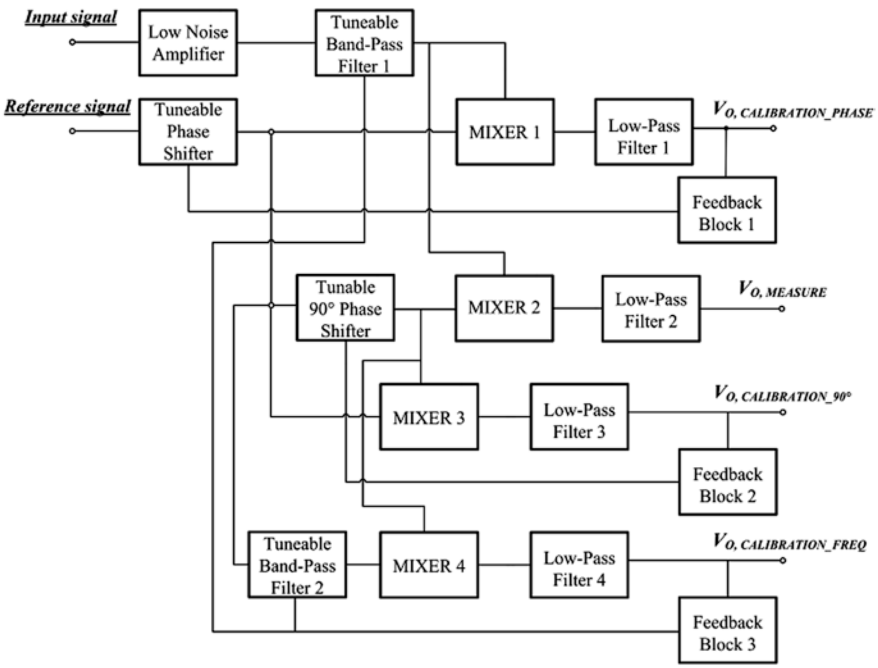

Fig. 1 Block scheme of the proposed automatic analog lock-in amplifier (when the three calibration outputs are zero, the $V_{O,MEASURE}$ value is proportional to the input signal amplitude)

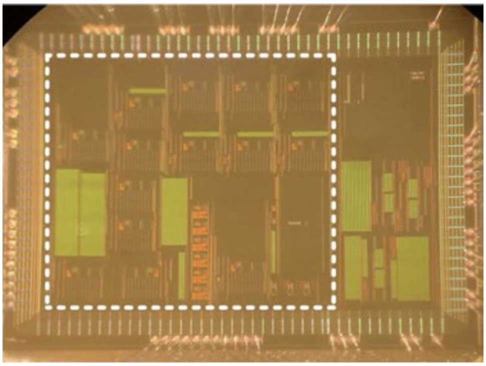

Fig. 2 Photo of the fabricated chip (the lock-in amplifier is highlighted in the *white dashed box*; its area is lower than 8 mm^2)

More in detail, the "in-phase" and "tuned" conditions are always constantly guaranteed by automatic operations of suitable feedbacks and control blocks which, at the same time, allow to properly extract the DC output signal, whose amplitude is proportional to that of the AC input noisy signal, as follows:

$$V_{O,MEASURE} = \frac{2AV_{Input\_signal}}{\pi}, \tag{1}$$

being *A* the voltage gain given by the low noise amplifier.

3 Experimentals with the Fabricated ASIC in CMOS Technology

Figure 3 reports measurement results achieved by an electrical characterization and employment of a commercial resistive gas sensor for the ethylene glycol detection. The results have demonstrated the system validity and its satisfactory performances, confirming the circuit capability to measure both noisy signal amplitudes, down to tens of nV, and reduced ethylene glycol concentrations. In particular, with respect to a resistive gas sensor interface implemented by the simple resistive voltage divider, sensitivity and resolution improvements, given by the proposed lock-in, are of a factor over than 100, so achieving a gas theoretical resolution value of about tens of ppb.

4 Conclusions

In this paper, a new analog lock-in amplifier, fully integrated in a standard CMOS technology ASIC, for automatic detection of very small and noisy signals in sensor applications, has been proposed. Its main advantage concerns its capability to perform, continuously, an automatic phase alignment and a frequency tuning allowing

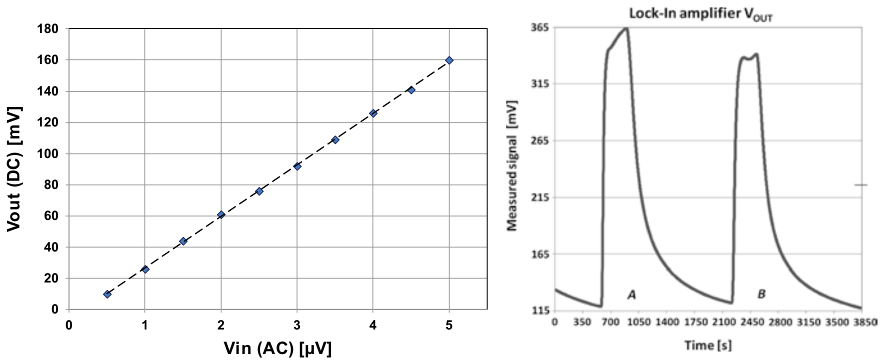

Fig. 3 Experimental results. On the *left*, measured DC output voltage (*dots*) vs. sample input AC signal amplitudes compared with theoretical calculations (*dashed line*, see (1); $f_0 = 11$ Hz). On the *right*, time response of the measured DC output voltage vs. time, for two different ethylene glycol concentrations (A = 4.8 ppm, B = 2.4 ppm) and employing a FIGARO TGS2600 as resistive gas sensor

the enhancement of the SNR and, thus, the improvement of the sensor interface sensitivity and resolution in the detection of very small physical/chemical quantities. Experimental results have shown the detection capability of very small and noisy signals, with a resolution in the order of tens of nV, making the proposed lock-in suitable for high-accuracy high-precision portable measurement systems.

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